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Final Report for Task 5796 - P.O. S-93074-E

Compton Observatory Observations of Clusters of Galaxies and Extragalactic Radio Sources.

Science Summary.

This task involved the investigation of the emission of clusters of galaxies, particularly those which contain extended radio emission, in the gamma-ray region of the spectrum. Observations were made of several clusters using the Compton Observatory EGRET instrument. For each cluster a measured flux or upper limit on the gamma-ray flux was obtained. In only one case, Abell 2199, was there a significant measured flux. This source is spatially confused with a known blazar in the field of view. The observation is consistent with all emission being from the blazar.

Essentially, this program has led to an improvement of an order of magnitude on the upper limits for the gamma-ray luminosity of clusters of galaxies. This result has important implications in the studies of the metagalactic cosmic ray background, the composition of the unseen matter in clusters of galaxies and the mechanisms by which some clusters of galaxies generate synchrotron radio emission over megaparsec scales. Preliminary results of this analysis has been published in the Proceedings of the Second Compton Symposium (AIP Conference Proceedings 304, p669, 1993) and in conjunction with later observations at the High Energy Astrophysics Division meeting of the AAS in November 1994. A final paper, funded separately, is being prepared for submission to the Astrophysical Journal.

Observations and Analysis:

Clusters observed specifically for the program included:

Abell 426
Abell 2162
Abell 2199
Abell 2255
Abell 2256
Abell 2319

The following clusters were analyzed using Compton Observatory archival data:

Abell 400
Abell 496
Abell 1060
Abell 1367
Abell 1656
Abell 2022
Abell 2052
Abell 2063
Abell 2462
Abell 2806
Abell 2870/2877
Abell 3526
Abell 3565
Abell 3574
Abell 4038
Abell 4049.

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These observations were processed using a combination of both instrument team software and software developed under this task. Analysis tasks included adding together data from overlapping viewing periods, developing tools to measure source and background counts, and determining confidence limits on detection. The EGRET team Like program was used in the final step of the analysis but all other software was developed under this program.

A High Energy Gamma Ray Survey of Clusters of Galaxies

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Abstract.

Clusters of galaxies may emit high-energy gamma rays due to a number of emission mechanisms including cosmic ray interactions with the intracluster medium and the annihilation of dark matter. We report on a search of measurements from the EGRET instrument aboard the *Compton* Observatory for gamma-ray emission from clusters of galaxies. This cluster survey includes a preliminary analysis of data from both pointed observations and the EGRET all-sky survey. Current upper limits are given and the cosmological implications of the observations are briefly discussed.

INTRODUCTION

The diffuse gamma-ray emission in our galaxy is thought to be due to interactions between cosmic rays and the interstellar medium and has been used to probe the properties of cosmic rays in the galaxy (Bloemen 1989; Fichtel *et al.*1989, and references therein). The presence of a relatively dense ($n \sim 10^{-3}cm^{-3}$) intracluster medium (ICM) in many clusters of galaxies means that similar mechanisms can generate gamma-rays at those extragalactic sites. Many rich clusters of galaxies also contain active galaxies that are known to be powerful sources of relativistic electrons. For these, and other reasons that we discuss below, EGRET observations of clusters of galaxies can place interesting constraints on high energy phenomena at extragalactic sites.

GAMMA RAYS FROM CLUSTERS OF GALAXIES

Estimating the density of cosmic rays

In models where the cosmic rays in the intracluster medium (ICM) are generated in the cluster galaxies, the number in a cluster is the number leaked from the constituent galaxies. If the generation of cosmic rays is proportional to optical luminosity, and we assume our Galaxy is typical, then

$$N_{cl} = N_{gal} \frac{t_H}{t_C} \frac{L_{cl}}{L_{gal}} \tag{1}$$

where t_H is the Hubble time, t_C is the confinement time of cosmic rays in the galaxy, N_{cl} is the number of cosmic rays in the cluster, and $N_{gal} \approx 10^{56}$ (Stecker and Tylka 1989), the number currently in our Galaxy. The L's are the respective optical luminosities.

Since the same emission mechanisms will be available in the cluster as in the galaxy, we can calculate the gamma-ray luminosity of the cluster as

$$L_\gamma = 3 \times 10^{42} \frac{t_H}{100\, t_C} \frac{L_{cl}}{50 L_*} \frac{N_{gal}}{10^{56}} \frac{M_{cl}}{2.5 \times 10^{14} M_\odot} \mathrm{ergs/s} \tag{2}$$

where we have assumed that the cosmic rays and gas are distributed in a King model of index ≈ 3 in the ICM.

For a cluster at 100 Mpc this is still a factor of about 6 too weak to be detected in a 500,000 second observation if the ratios are unity. However, given the considerable uncertainties in many of the quantities (particularly in the confinement time) that go into this luminosity, gamma rays from leaked cosmic rays may still be detectable by EGRET, particularly if the Hubble constant is large (so that clusters are relatively nearby). Even if individual clusters are not visible, a sample of clusters may show a significant excess of positive deviations.

Cluster Radio Halos

Radio observations indicate that relativistic electrons are present in the ICM of at least half a dozen clusters (Hanisch 1982). These clusters contain extended regions of low radio surface brightness that are associated with the cluster as a whole rather than individual active galaxies. A well studied example is in the Coma cluster where the halo has a scale size of roughly 1 Mpc and a steep power-law spectrum ($\alpha \sim 1.3$, *e.g.*, Kim et al. 1990). The radio measurements are best explained by synchrotron emission from relativistic electrons in an intracluster magnetic field.

The spatial extent of Coma-type halos has led to difficulties for understanding their origin. It is natural to assume that the halo is powered by electrons that leak out of active radio galaxies. However, Jaffe (1977) has shown that these leakage models have difficulty accounting for the size of the radio halos. The crux of his argument is that if the bulk drift velocity of electrons is limited to the Alfven speed (Wentzel 1974) then the time for electrons to diffuse to the outer parts of the radio halo exceeds the synchrotron-Compton loss timescale by at least two orders of magnitude. So while some energetic electrons must certainly leak into the ICM from active galaxies, the bulk of the radiating electrons must be generated in some other manner. Two approaches to the generation of relativistic electrons within the cluster ICM have been explored. The first approach, employed by "primary electron" models, assumes that the electrons are accelerated *in situ* by either shocks or turbulence in the ICM (Schlickeiser et al. 1987). The second approach, employed by "secondary electron" models, assumes that the radiating electrons are generated when leakage cosmic ray protons, whose much longer radiative lifetimes allow them to fill the cluster volume, collide with thermal ICM nuclei (Dennison 1980).

Inasmuch as both types of models for Coma-type halos require the presence of high-energy particles in the ICM, it is of interest to examine gamma-ray production by these particles as they interact with the thermal gas required by cluster x-ray observations. By combining the ICM density measurements provided by x-ray observations and the shape of non-thermal electron spectrum provided by the radio measurements, one can calculate the gamma-ray flux given an assumed magnetic field strength. For the Coma cluster, the absence of a hard component of Compton x-rays limits the minimum field strength to 0.1μG (Rephaeli *et al.* 1987). For primary electrons models this yields a predicted maximum nonthermal bremsstrahlung flux at 100 MeV of $\sim 10^{-8} cm^{-2} s^{-1} MeV^{-1}$, which would be difficult to detect with EGRET. On the other hand, secondary electron models predict a detectable pion decay flux from Coma if the field strength is less than 0.5μGauss (Vestrand 1990). A detection of Coma by EGRET would therefore be strong evidence for a reservoir of cosmic-ray protons in the ICM.

Metagalactic cosmic rays

If local cosmic rays are of metagalactic origin, then the flux of cosmic rays in clusters should be easily detectable. Using simple geometric arguments

$$\frac{B_{cl}}{B_{gal}} = \frac{\rho_{cl}}{\rho_{gal}} \frac{s_{cl}}{s_{gal}} \tag{3}$$

where the densities are of the ICM versus ISM and s is the scale of the system. Since the product of these ratios is about unity, and the clusters fill a significant fraction of an EGRET resolution element, clusters should be visible.

Annihilation of dark matter

It is generally believed that most of the matter in clusters is contained in some form of dark matter whose nature is unknown. There are many possibilities for the nature of this matter including a number of exotic particles which may occasionally decay to gamma rays and other products during encounters (see for example Silk and Bloemen 1987; Rudaz and Stecker 1988). While it is likely that local Galactic constraints on the flux of gamma rays rule out a significant contribution from this process, there is some chance that such decays could be measurable in clusters.

To within a geometric factor the relative surface brightnesses of the Galaxy and clusters are

$$\frac{B_{cl}}{B_{gal}} \approx \frac{< n^2_{x_{cl}} >}{< n^2_{x_{gal}} >} \frac{s_{cl}}{s_{gal}} \tag{4}$$

where the n's are the densities of the exotic particles and the s's are the scale lengths. The geometric factors of order unity are indeterminate without a knowledge of the distribution of dark matter and could conceivably favor detection in clusters.

If dark matter does not participate in the formation of galaxies to the extent that the ratio $\frac{<n^2_{x_{cl}}>}{<n^2_{x_{gal}}>} > \frac{10\mathrm{kpc}}{1\mathrm{Mpc}} = .01$, then the cluster emission of annihilation products would be brighter than the Galaxy's. If the average square of the density of exotic particles is enhanced a factor of 100 or more in the Galaxy above the corresponding average in clusters, then the Galactic surface brightness will be greater than clusters (and will of course extend over a larger area). Much larger enhancements are seen in the visible matter. Still, given that dark matter is unlikely to participate in dissipative processes, its detection is not completely infeasible and with so little understood about its nature, any clues would be important.

THE OBSERVING PROGRAM

The survey involves the analysis of both archival information from the CGRO archive, and pointed observations of the most promising candidates for the detection of gamma rays. The observing program was begun in Phase 2 with several targets observed in periods 201 and 202. Further observations are scheduled for Phase 3 including a much deeper observation of the Coma cluster.

RESULTS

A simple aperture photometry technique has been used to determine the flux limits in Table 1. An annulus around the source region is chosen for background. The counts in this background region are multiplied by the ratio of the total exposure in the source region to the exposure in the background annulus and subtracted from the counts in the source region. Any excess counts are then attributed to the source. The source region is a circle of radius 6.7°. The background annulus has an inner radius of 9.5° and an outer radius of 13.4°. Only high quality photons with energy > 70 MeV were used in the analysis. The flux is computed using the average exposure over the source region. Note that the average exposure in the region is related to the total exposure by $< E > = (\int E(\Omega) d\Omega)/\Omega$, where the integral over the solid angle of the source region is the total exposure in that region.

With the exception of A2199, none of the clusters was detected. A2199 is confused with the AGN 4C38.41 about a degree away (Mattox *et al.* 1992). Since the emission is seen to undergo strong variations on a week timescale most of the flux must be attributed to a non-extended source. The flux we obtain for this source agrees well

Cluster	D ($H_0 = 50$) Mpc	Viewing Periods	Flux Limit (>100 MeV) 10^{-7}(cts s^{-1} cm^{-2})	Luminosity Limit (>100 MeV) (10^{44}ergs s^{-1})
A400	139	21.0	1.9	4.0
A426(Perseus)	110	15.0	–[1]	–
A496	192	29.0	5.0	20.
A1060	68	0.7	4.5	2.3
A1367	129	3.0,4.0,11.0		20.
A1656(Coma)	140	3.0,4.0,11.0	1.3	2.8
A2022	330	9.5,201.0,202.0	2.3	27.
A2052	210	24.0,24.5,25.0	2.0	9.6
A2063	200	24.0,24.5,25.0	4.0	17.
A2162	190	9.5,201.0,202.0	6.2[2]	24.
A2199	180	9.5,201.0,202.0	10[2]	35.
A2255	480	9.5,201.0,202.0	2.8	70.
A2256	360	9.5,201.0,202.0	1.5	21.
A2319	338	2.0,7.0	–[1]	–
A2462	420	9.0,13.5,19.0	1.5	29.
A2806	160	9.0,10.0,13.5	1.4	3.9
A2870/A2877	150	9.0,10.0,13.5	6.2	15.
A3526	66	12.0,14.0	3.2	1.5
A3565	66	12.0	2.0	0.94
A3574	84	12.0	5.4	4.1
A4038	170	9.0,13.5	1.4	4.4
A4049	170	9.0,13.5	1.7	5.3

[1] Confused with Galactic flux.

[2] Confused with 4C+38.41.

Luminosity limits assume a photon power law index of 2.2. All limits are 2σ fluctuations.

Table 1. Clusters observed.

with that of the EGRET team. Upper limits on the flux of clusters which we have analyzed are described in Table 1. The simple aperture photometry approach we have used fails for A426 and A2319 which are at low galactic latitude. The background for these sources must be handled in a more sophisticated fashion which will be possible with the likelihood technique.

DISCUSSION

The investigations we have so far presented are only preliminary. We anticipate that limits perhaps an order of magnitude deeper can be made with better analysis. Sophisticated likelihood analysis programs should soon become available and deeper observations of Coma will be made in Phase 3. Nevertheless, some of our results are already interesting.

The non-detection of clusters drives another nail in the coffin of metagalactic origin for cosmic rays and supports the findings of Sreekumar *et al.* (1992) who looked at emission from the Magellenic clouds.

The limits on the emissivity of the Coma cluster increase the lower limit of the intracluster field strength by a factor of five to $\sim 0.5\mu G$ if the radio halo is powered by secondary electrons. Using this lower limit in a simple turbulent cell model for the cluster field structure, the observations of the Faraday depth for polarized radio sources (Kim *et al.* 1990) would require at least 4 turbulent cells per gas core radius. We estimate that the deeper exposure for Coma that should occur during the Phase 3 observations will allow us to detect pion gamma-rays even if the field strength is $\sim 1\mu G$. Failure to detect Coma at that sensitivity level would force secondary electron models into a rather small region of parameter space.

Using the simple model discussed above the confinement times for cosmic rays in the cluster galaxies must be $> 10^7$ years. This is consistent with current estimates of the confinement times of several times 10^7 years from analysis of the isotopic composition of local cosmic rays (*e.g.*, Webber *et al.* 1990). It should be possible to get very close to those limits with longer observations and enhanced analysis techniques.

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